Advances in Runaway Electron Control and Model Validation for ITER

by

C. Paz-Soldan[1]

with contributions from:

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[5] Max-Planck Institute, Greifswald
[6] Princeton Plasma Physics Laboratory
[7] Chalmers University

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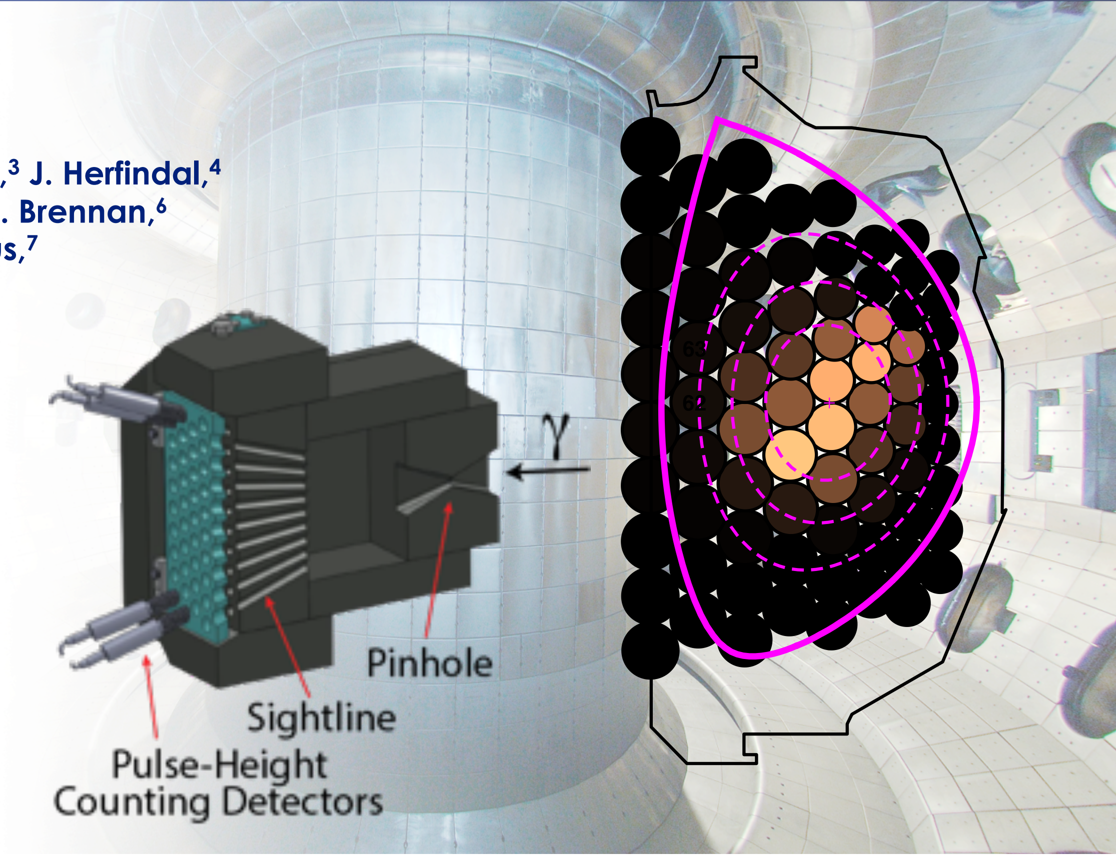


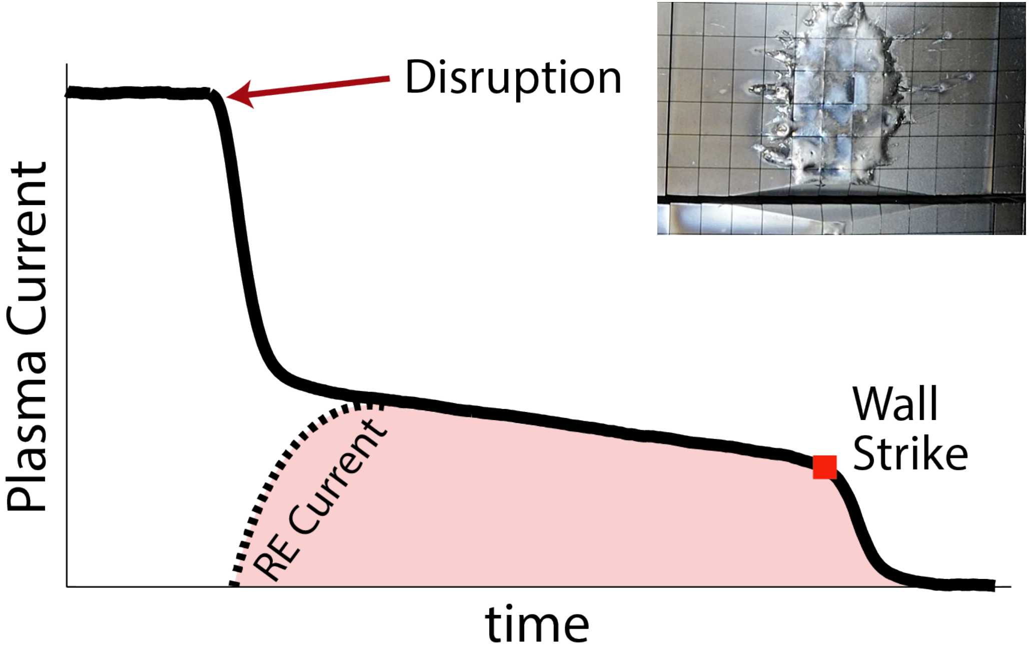
DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

Runaway Electron (RE) Control is an Existential Concern for Fusion-Grade Tokamaks

- **REs are formed after a disruption and can damage the first wall**

RE Strike on JET
C. Reux et al



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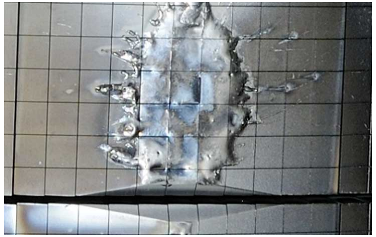

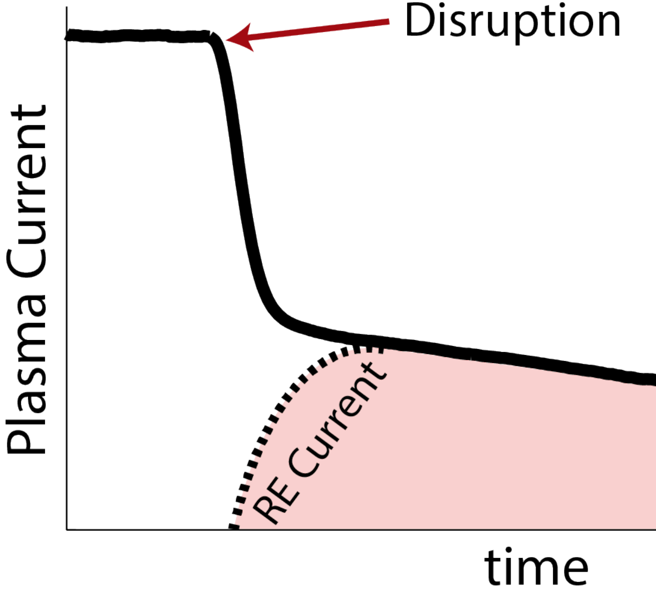

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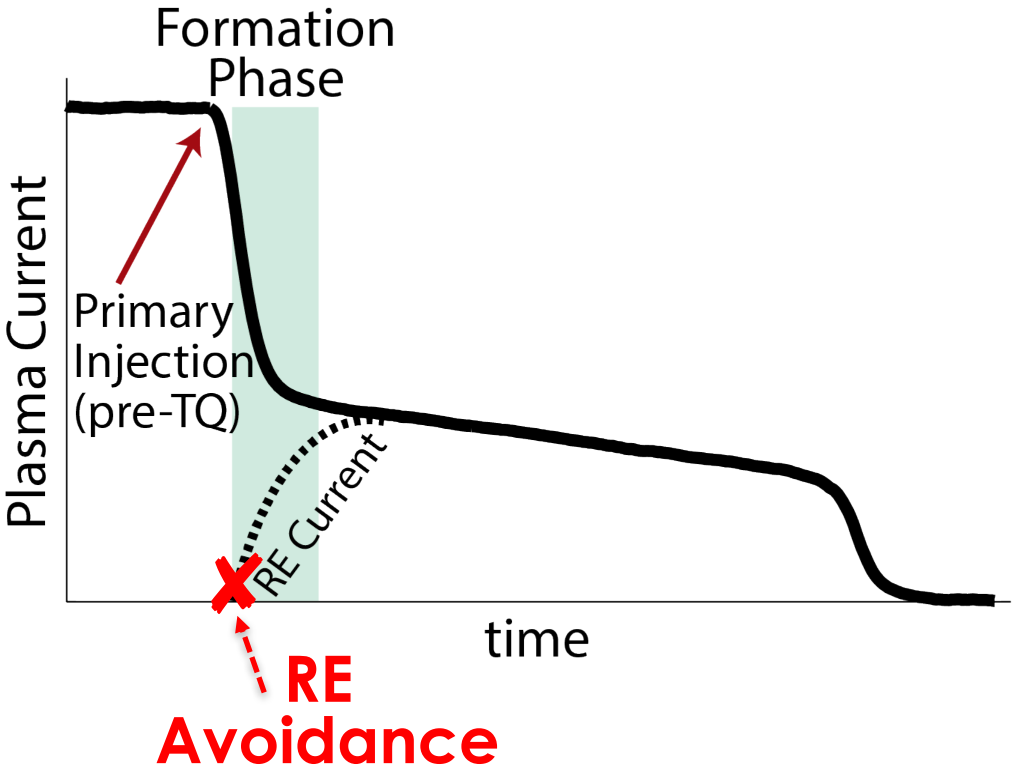
- **Talk presents experiment and modeling advances for the:**
    1. Formation Phase: Avoidance



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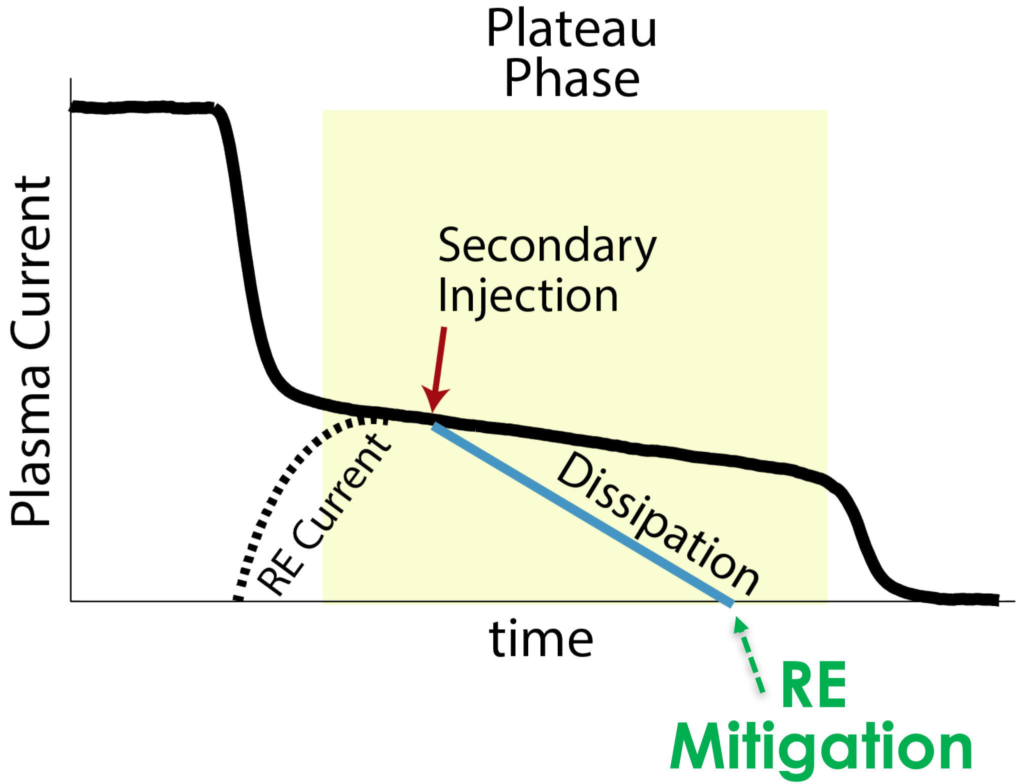

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- **REs are formed after a disruption and can damage the first wall**
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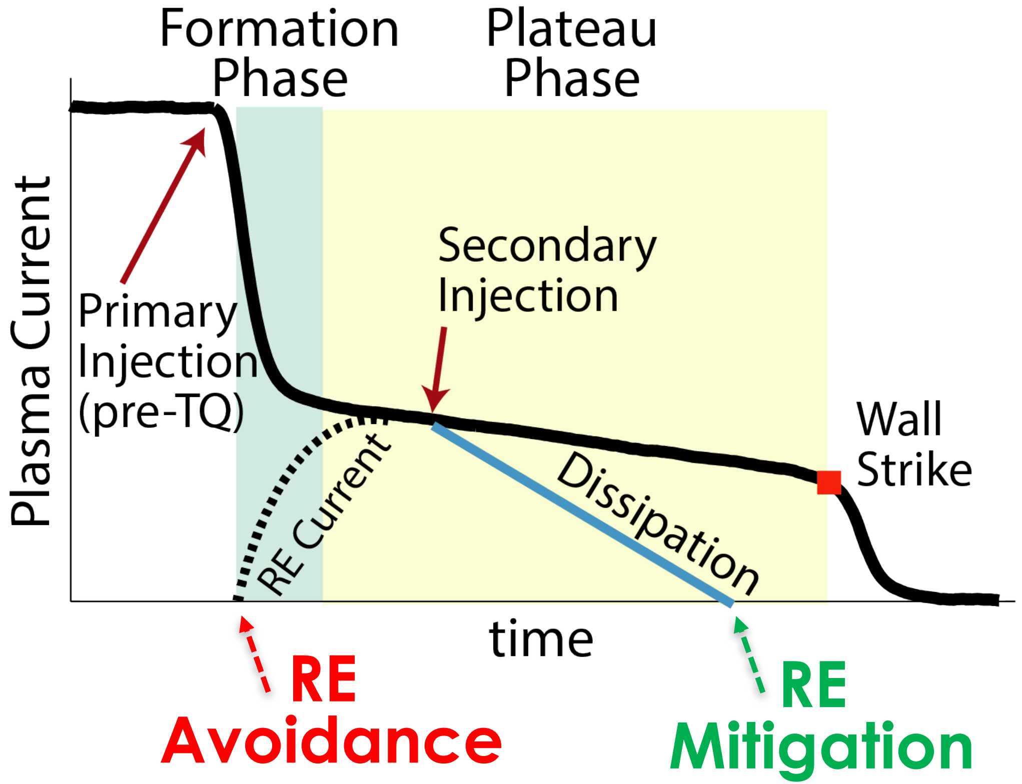
  2. Plateau Phase: Mitigation

- **Limited opportunity for empirical tuning of RE mitigation**

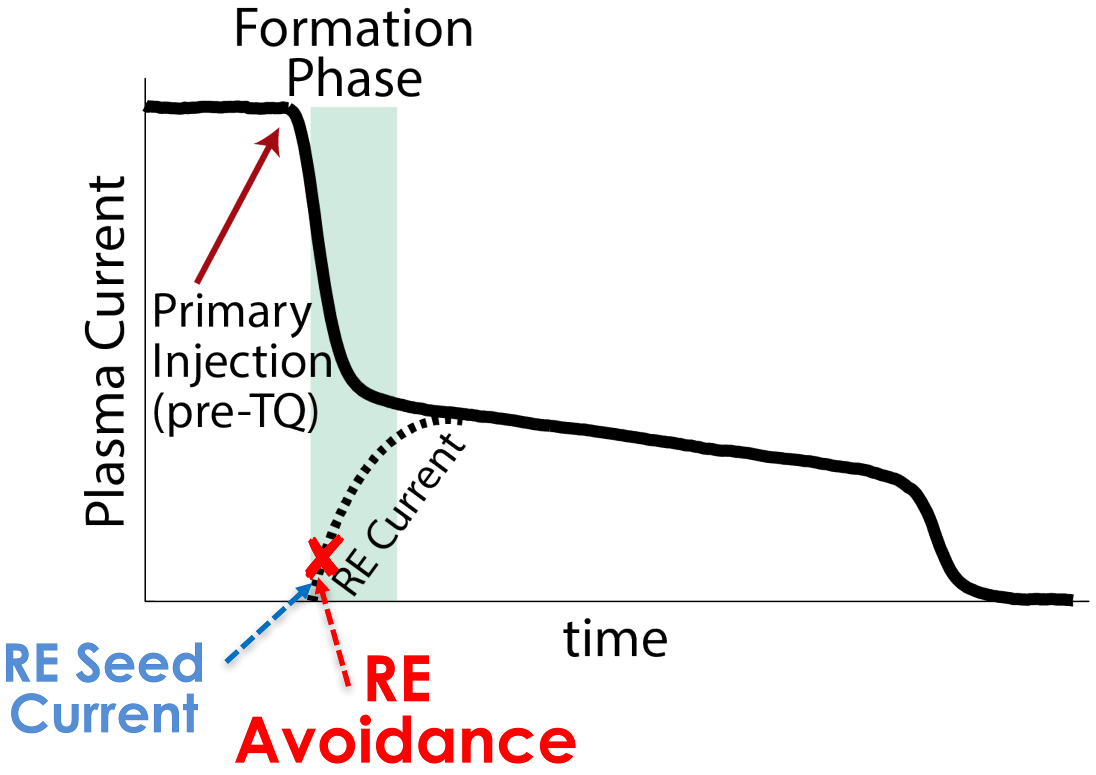
Validated predictive modeling of RE control is essential



RE Formation Phase Offers the Opportunity to Completely Avoid RE Issues

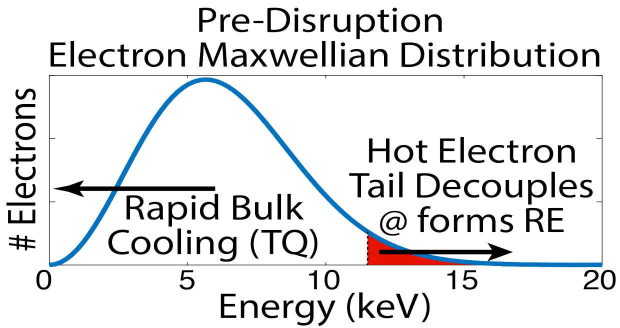
1. **Can we predict the initial (seed) RE current?**

2. **Do we have options to avoid the RE plateau phase?**



Experimental RE Seed Current of ~ 1 kA Estimated … *Far* Away from Hot-Tail Theory Predictions

- **Hot-Tail mechanism[1] expected to dominate RE seed production in ITER**



[1]Smith et al, PoP 2008

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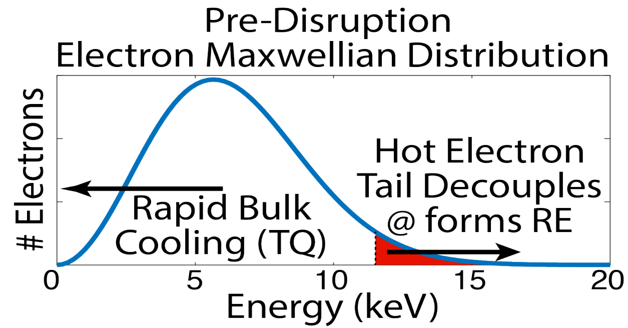
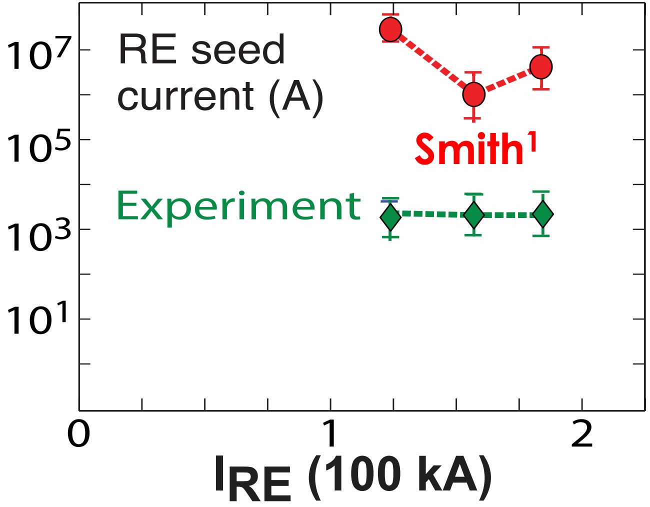


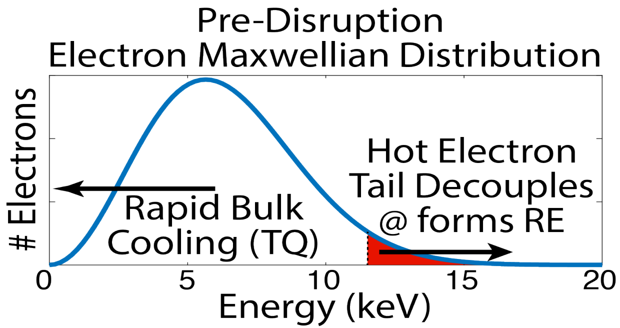


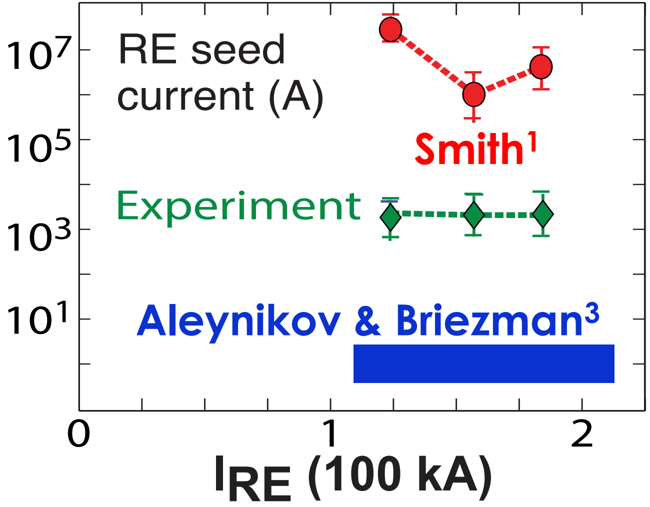
[1]Smith et al, PoP 2008
[2]E. Hollmann et al, NF 2017

Experimental RE Seed Current of ~ 1 kA Estimated … *Far* Away from Hot-Tail Theory Predictions

- **Hot-Tail mechanism[1] expected to dominate RE seed production in ITER**
- **Early theory[1] exceeds experimental estimates from pellet ablation light[2]**
- **Recent theory[3] self-consistently treats plasma cooling with RE seed formation but now under-predicts RE seed**

Open area for improvements
… Pellet interaction missing



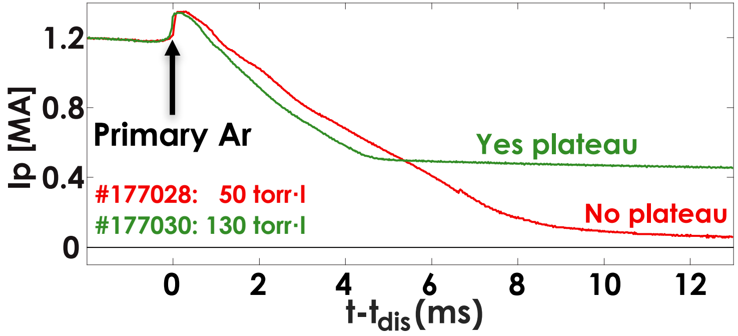


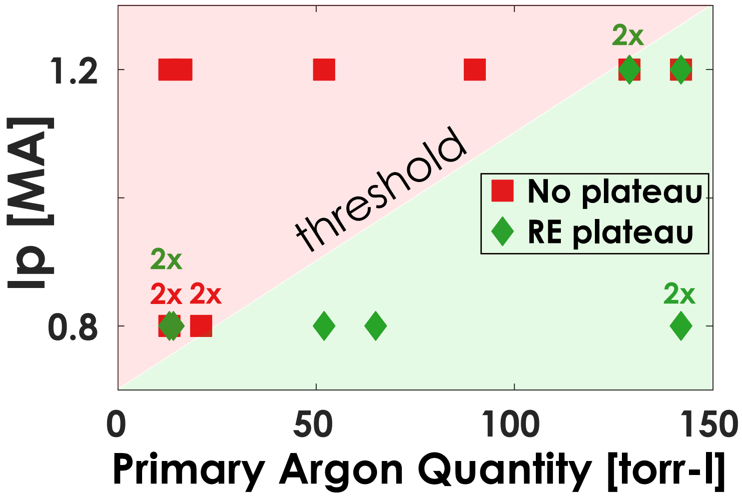
[3]P. Aleynikov, B. Breizman, NF 2017 [1]Smith et al, PoP 2008
[2]E. Hollmann et al, NF 2017

DIII-D Sometimes Experiences Unreliable RE Formation … Threshold Behavior Observed

- **RE formation in DIII-D can be unreliable**
  - Corollary: RE plateaus **avoidable**

- **Threshold for RE avoidance seen in primary Argon quantity and Ip**





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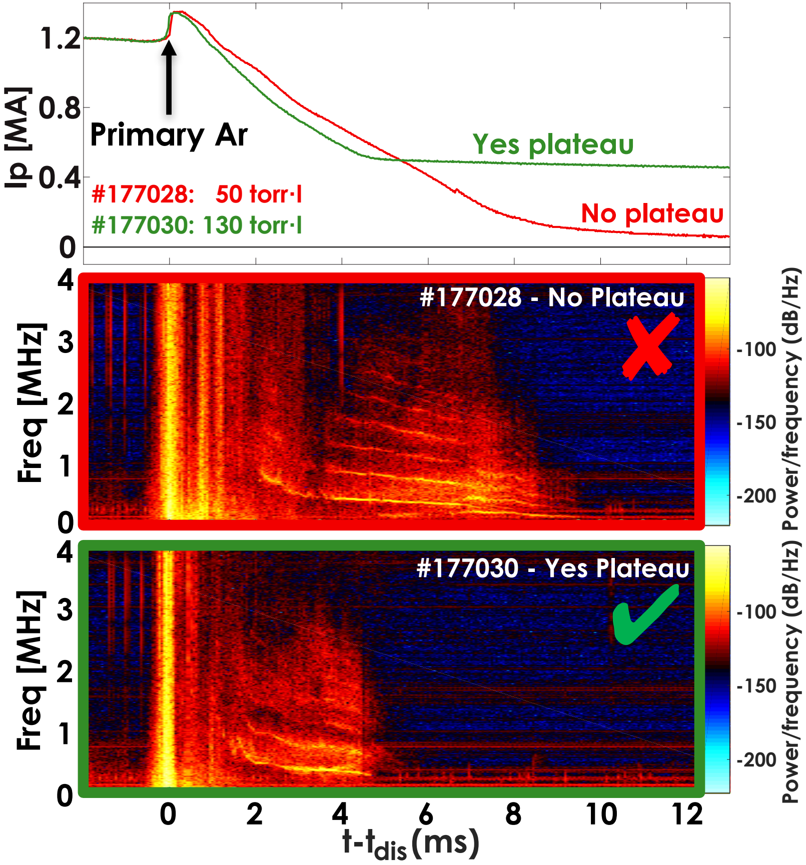
Intense Alfvenic Instabilities (~ MHz range) Observed During RE Plateau Formation, Correlates with Avoidance

- **Avoided RE plateaus correlate with intense & coherent MHz-frequency modes**
  - Candidate: compressional Alfven wave driven by REs



A. Lvovskiy et al, PPCF (in press)

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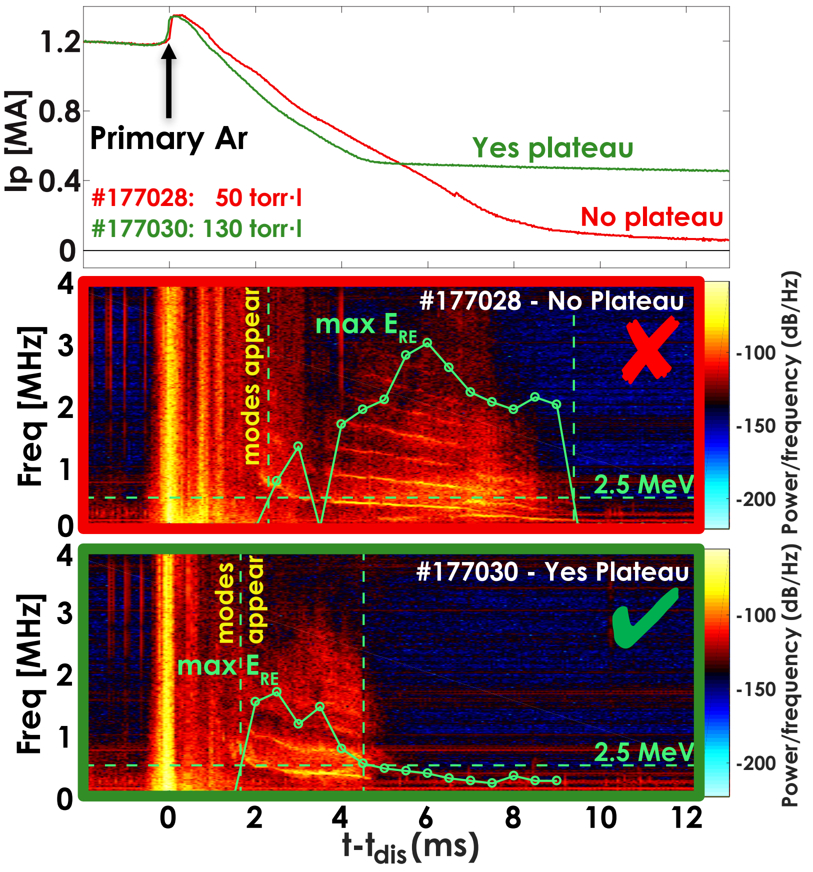

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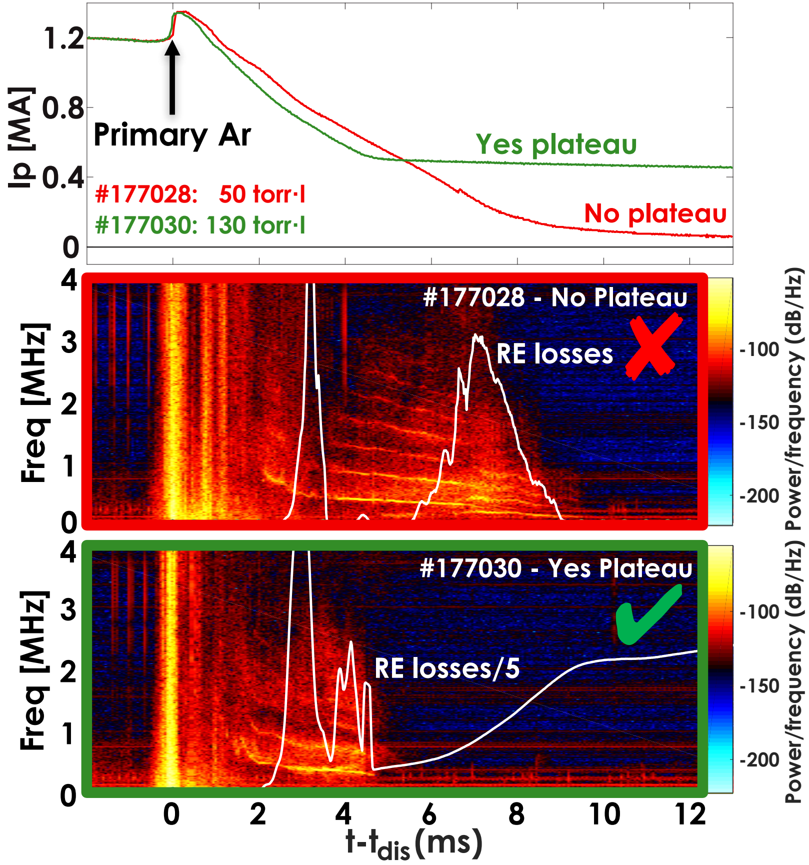
  - Candidate: compressional Alfven wave driven by REs
- **Hard x-ray spectrometry indicates critical RE energy for mode**
- **Modes causal to hard x-ray bursts indicating some RE loss**
  - Can this explain avoided plateau?



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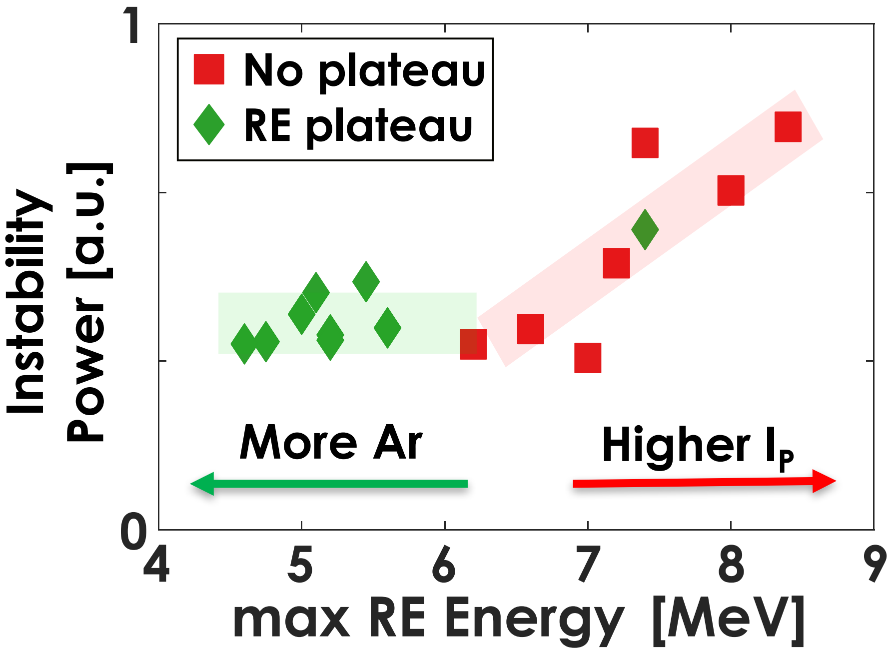
Excitation of Alfvenic Instabilities May Explain Critical Argon Quantity and Ip Dependence for RE Avoidance

- Increasing Argon *reduces* high-energy REs & suppresses modes
  - ➢ RE plateau forms
- Increasing I_p increases high-energy RE & enhances modes
  - ➢ RE plateau avoided
- Surprising result challenges assumptions about instability

Is neglect of instabilities justified?



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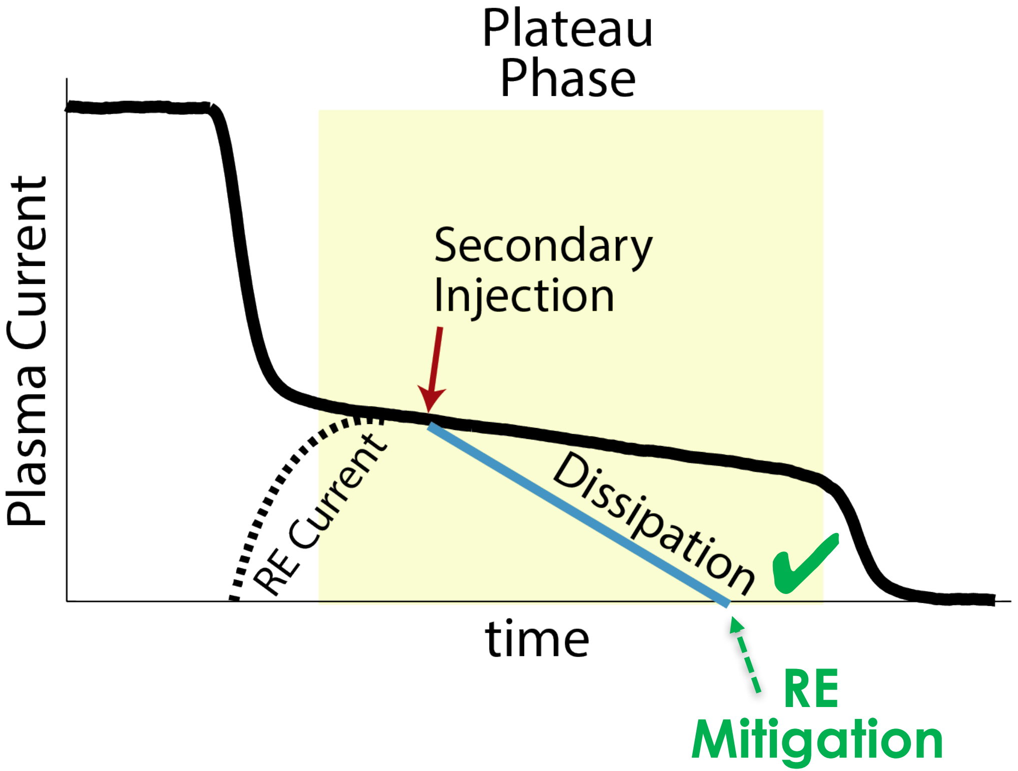
Secondary Injection (of High-Z Material) during Plateau Phase is Main Defense for ITER

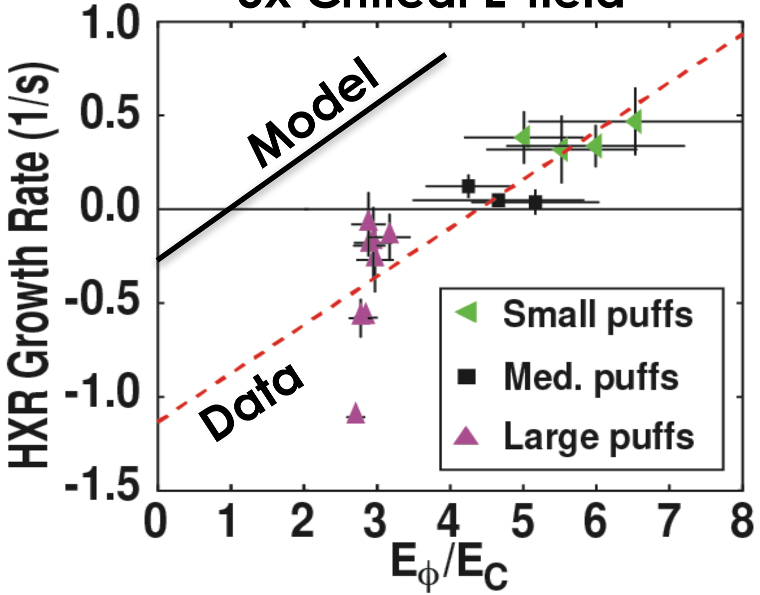
1. **Do we understand RE distribution function and dissipation rate?**

2. **How can the dissipation rate be increased?**



Resolving Anomalous RE Dissipation is a Key Issue … Seen in Multiple Experiments and Regimes

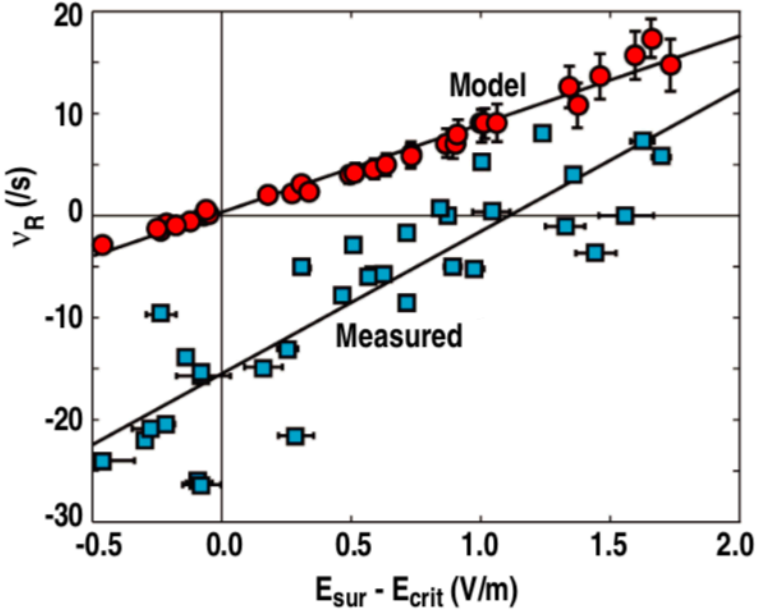
5x Critical E-field



R. Granetz et al, Phys Plasmas 2014

Ohmic Flat-top

10x Critical E-field



E. Hollmann et al, Nucl Fusion 2011

Post-Disruption

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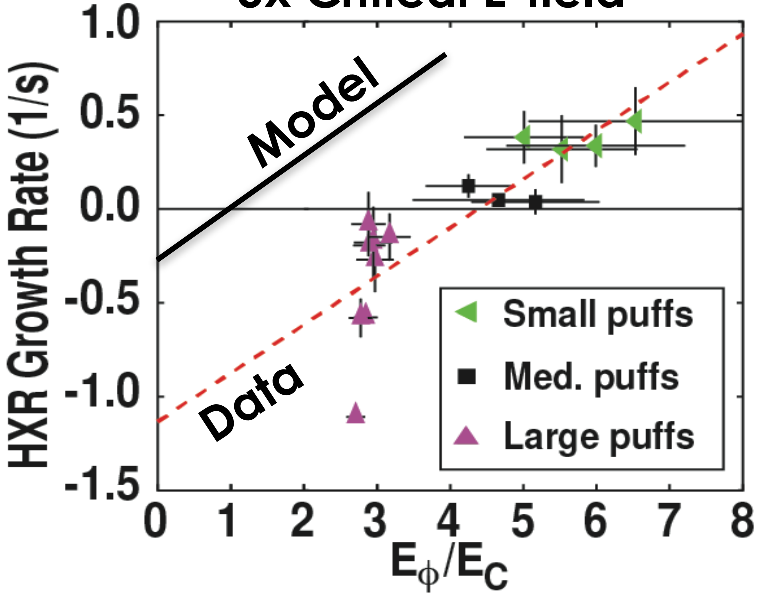

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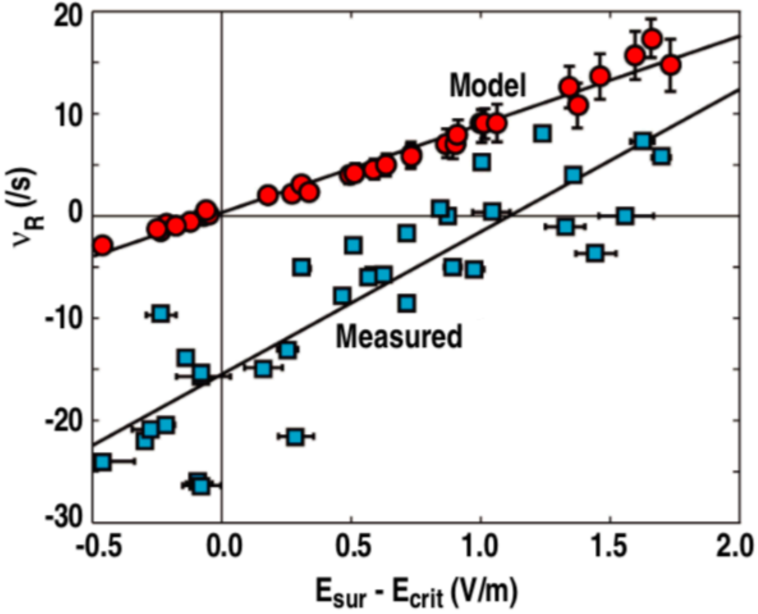

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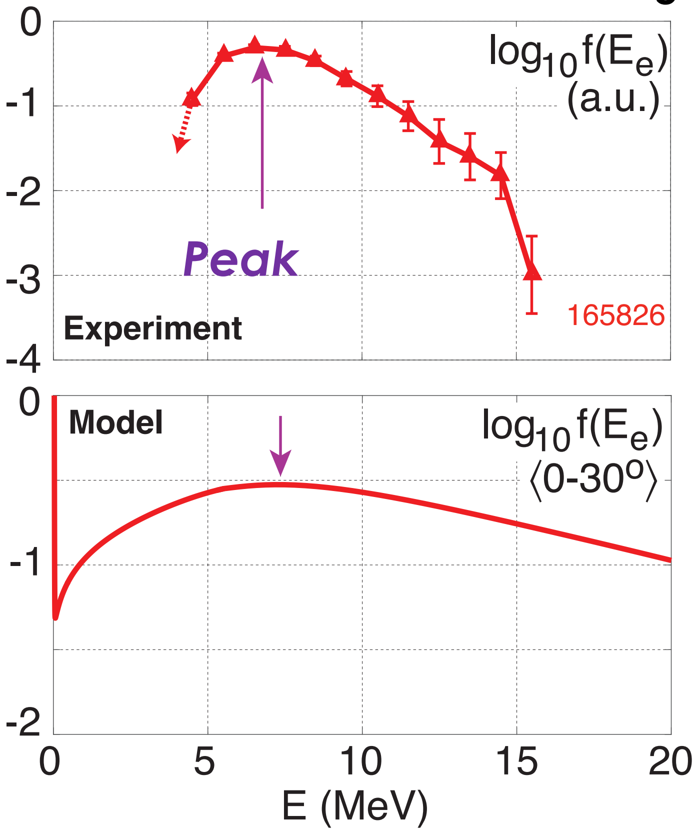
Direct Comparison of Experimental and Theoretical RE Distribution Functions Confirm Non-Monotonicity

- **RE distribution obtained from:**
  - HXR spectroscopy (experiment)
  - 0-D Fokker-Planck (model)
- **Both peak at similar energies**
- **High-energy falls off faster in experiment**

1-D RE distribution via Bremsstrahlung



C. Paz-Soldan et al, PRL 2017

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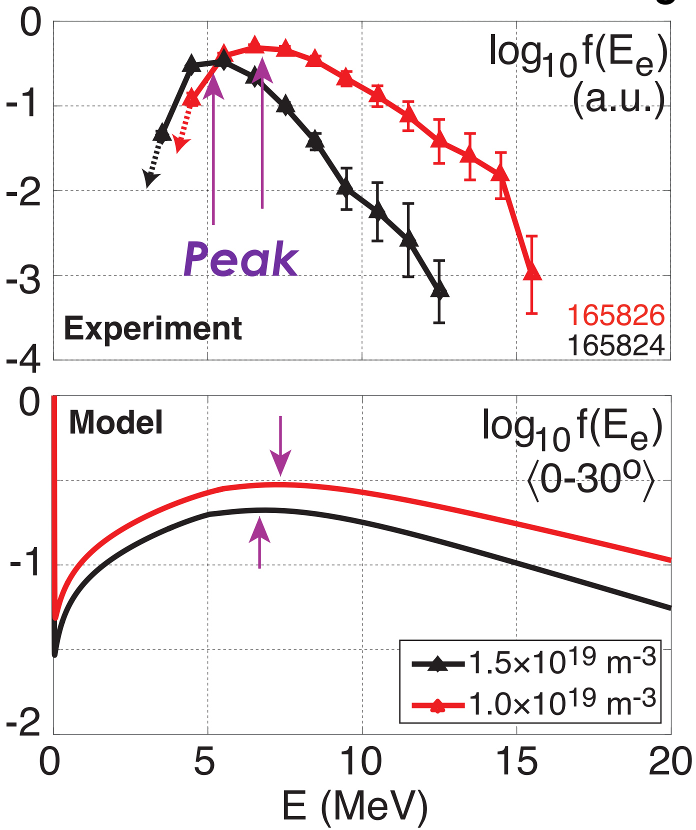

C. Paz-Soldan et al, PRL 2017

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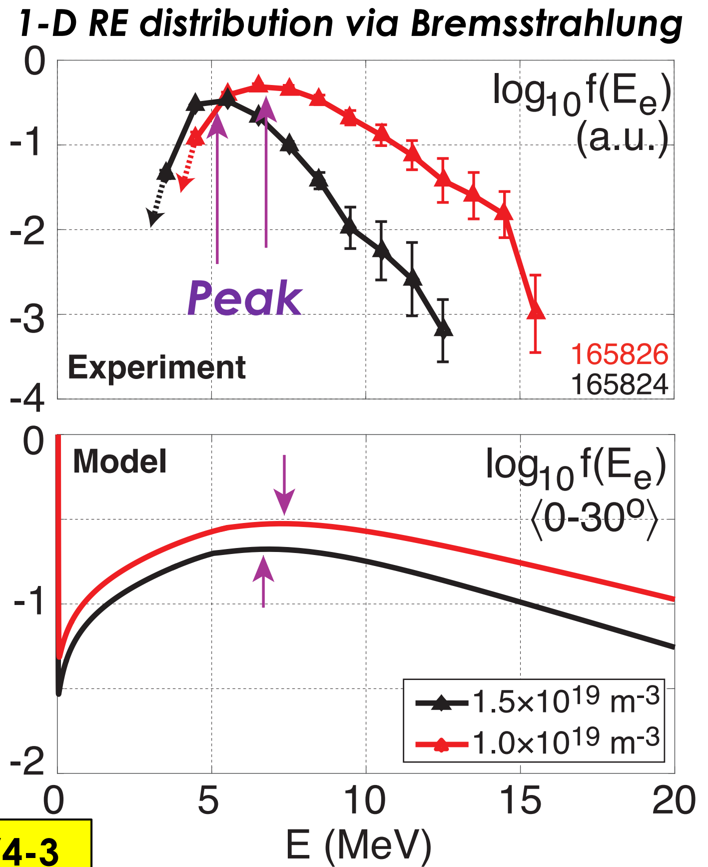
- **Synchrotron-based RE validation to be discussed later this session**



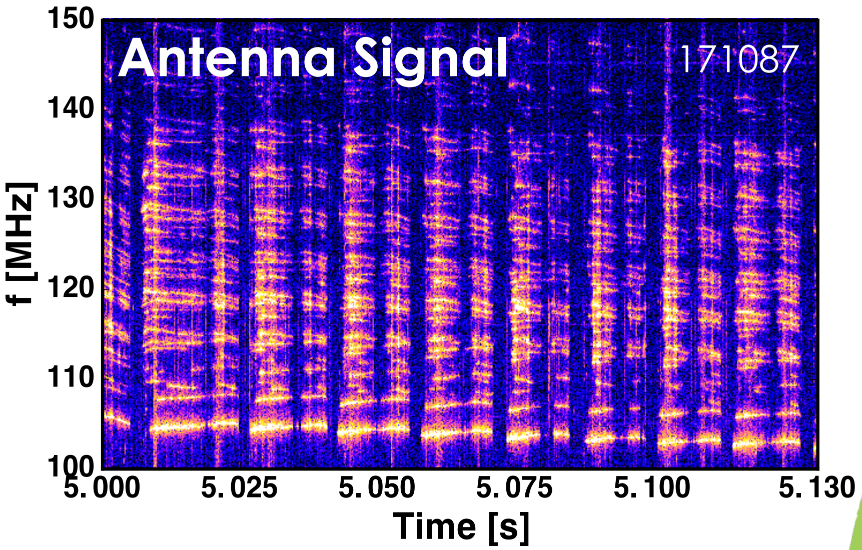
C. Paz-Soldan et al, PRL 2017

Synchrotron: del-Castillo-Negrete, TH/4-3

High Frequency Antenna Reveals Kinetic Instabilities at ~100 MHz in Ohmic Flat-top RE Experiments

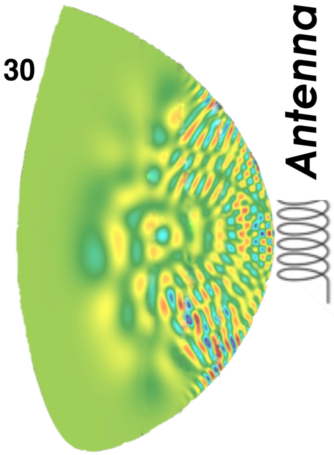
- **Instability intensity proportional to RE population size**

- **Identified as whistler wave by varying dispersion relation terms**



- **De-stabilized (in part) by non-monotonic distribution function features**
  - ~ 100 MHz modes predicted (and observed)
  - ~ GHz modes also predicted (no diagnostic)

Whistler Structure

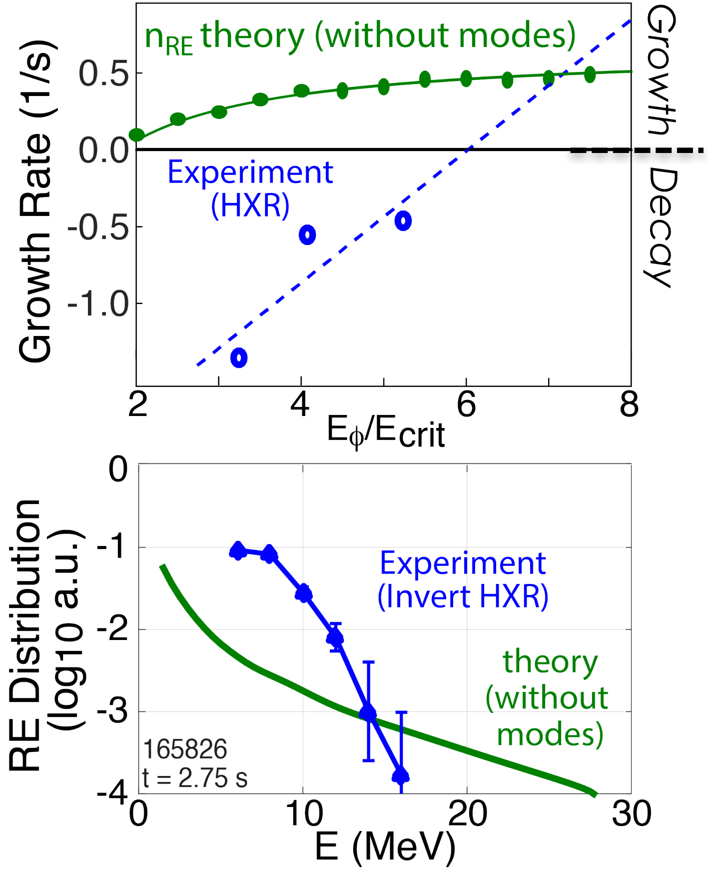


D. Spong, TH/P8-17 & K. Thome, EX/P6-29

D. Spong et al, PRL 2018

Inclusion of Kinetic Instability Recovers Anomalous Dissipation and Improves Distribution Agreement

- **Experiment identified dissipation rate and distribution function anomalies**



C. Liu et al, PRL 2018

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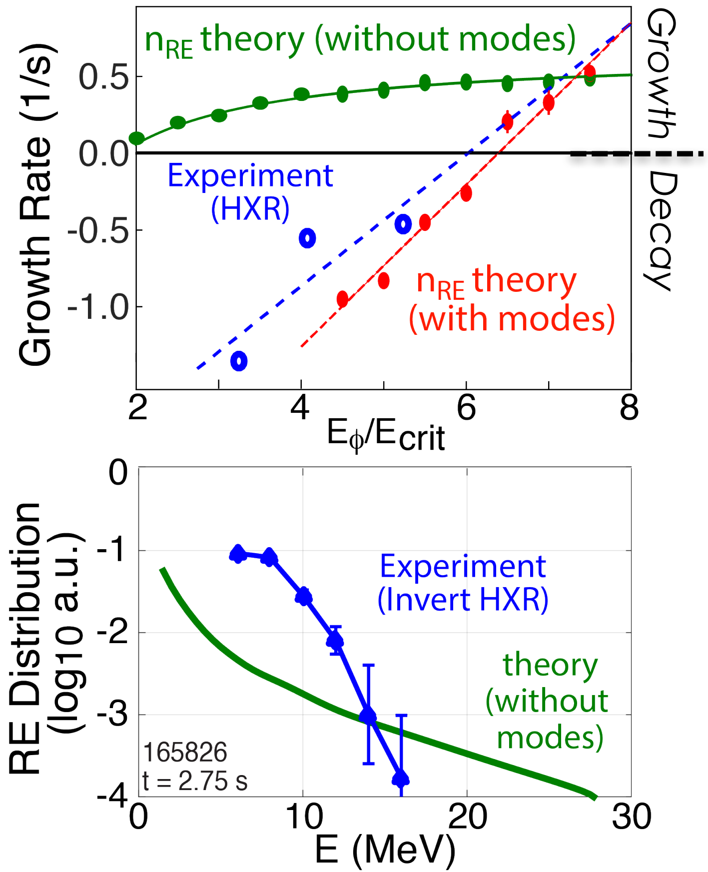
  - Possible resolution to reported discrepancy



C. Liu, TH/P8-16

C. Liu et al, PRL 2018

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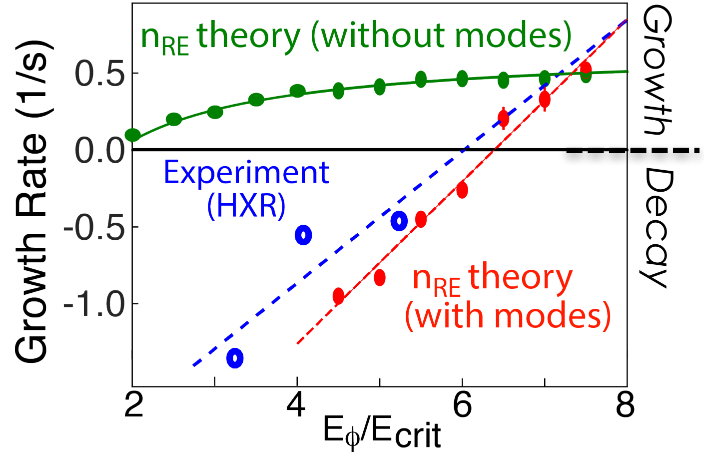
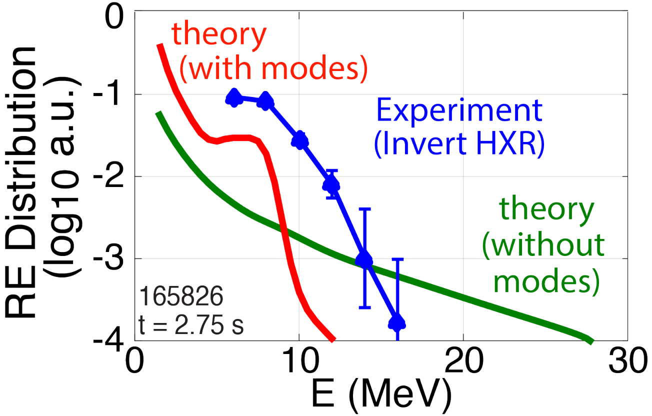
  - Possible resolution to reported discrepancy
- **Much better match of RE distribution slope with kinetic instability included**



Kinetic instabilities essential to understand Ohmic flat-top regime dynamics

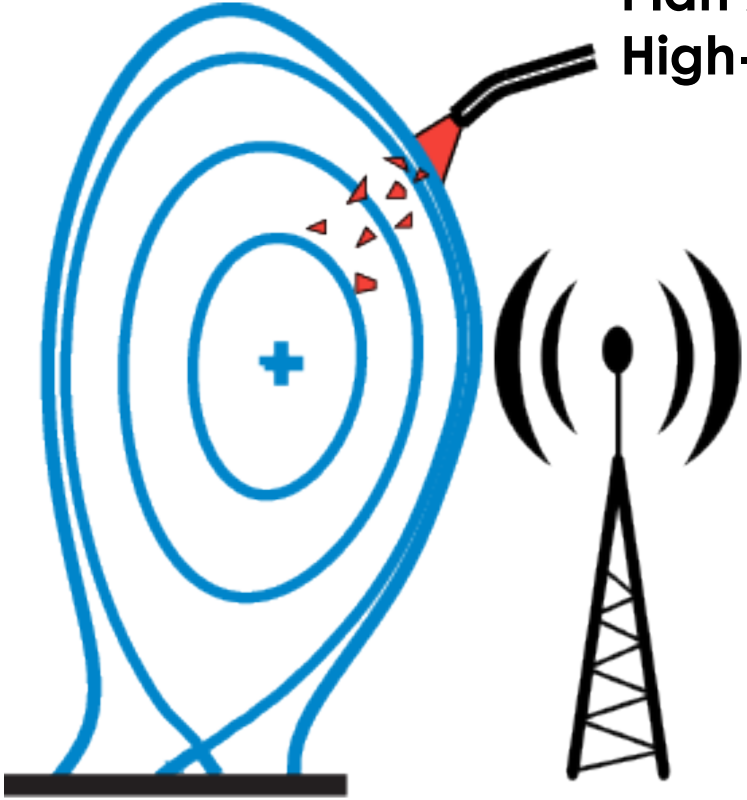


C. Liu, TH/P8-16

C. Liu et al, PRL 2018

Are Instabilities an Alternate Path to Dissipate the RE Plateau?

- Secondary injection expected to be high-Z material (Argon)
- Can kinetic instabilities offer an alternate path to control?

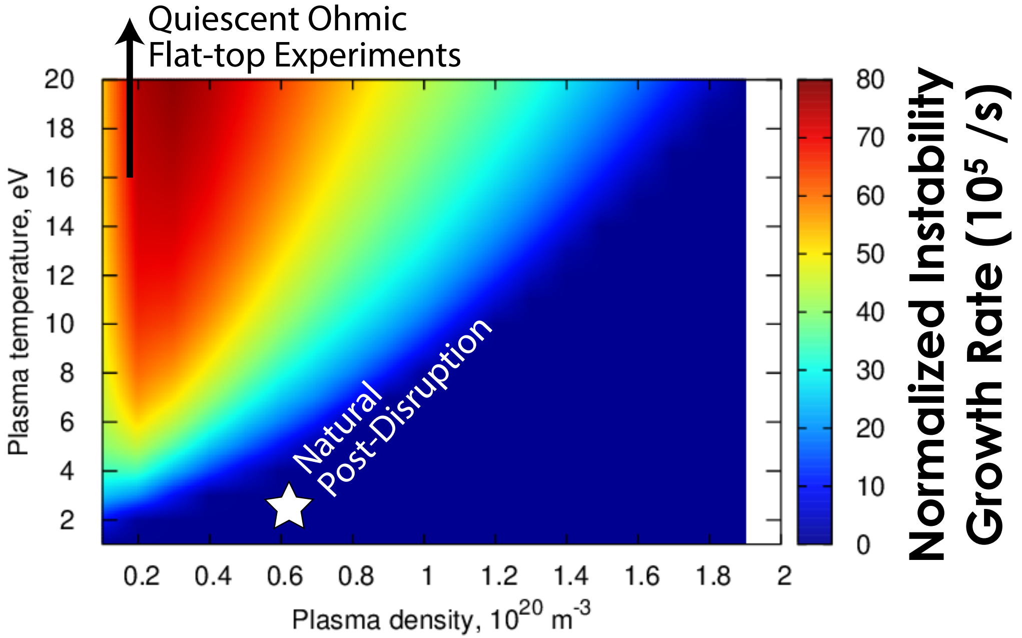


Plan A:
High-Z Injection

Plan B:
Instabilities?
(natural or driven)

Exploitation of Kinetic Instability Easiest in Collisionless Plasmas

- **Stability diagram calculated[1] for high-freq kinetic instabilities**



[1]**P. Aleynikov, B. Breizman, NF 2015**

Exploitation of Kinetic Instability Easiest in Collisionless Plasmas

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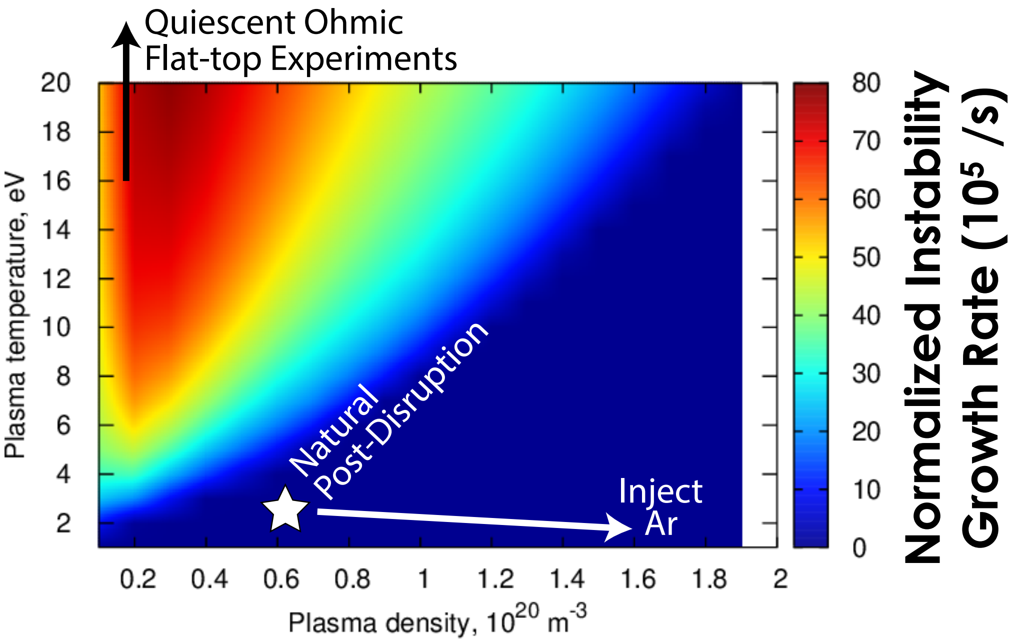
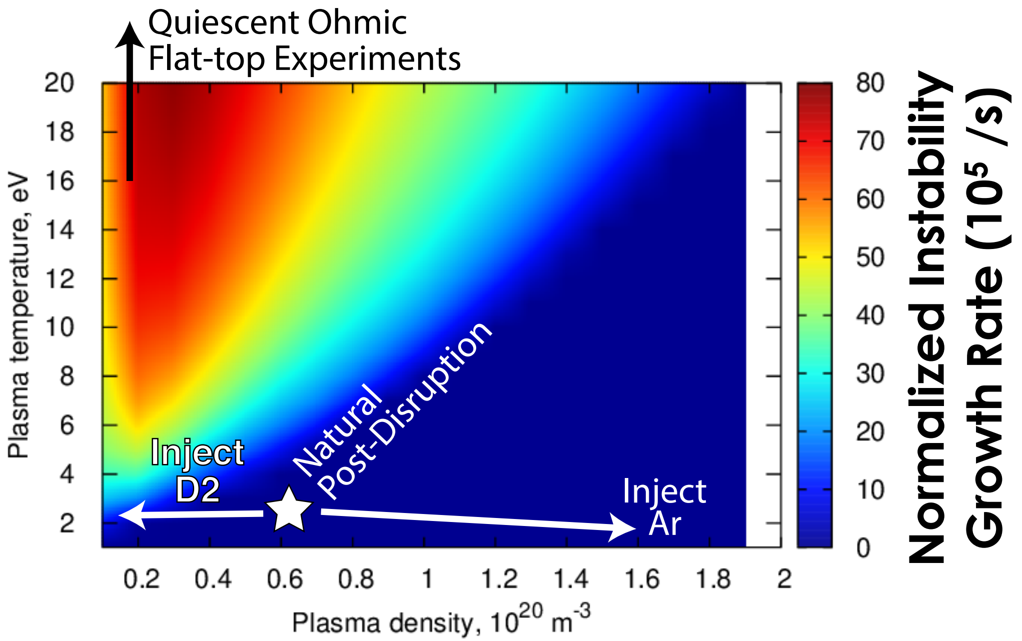
- **High-Z (Ar) injection likely to suppress instabilities via collisional damping**
  - However - counter example already shown: ~ 1 MHz modes
  - Stability analysis[1] needs to be amended for Alfvenic modes



[1]P. Aleynikov, B. Breizman, NF 2015

Exploitation of Kinetic Instability Easiest in Collisionless Plasmas – Achievable by Injecting Deuterium

- **Stability diagram calculated[1] for high-freq kinetic instabilities**
- **High-Z (Ar) injection likely to suppress instabilities via collisional damping**
  - However - counter example already shown: ~ 1 MHz modes
  - Stability analysis[1] needs to be amended for Alfvenic modes
- **Low-Z (D_2) injection reduces density[2] and thus damping**



[1]P. Aleynikov, B. Breizman, NF 2015
[2]D. Shiraki et al, NF 2018

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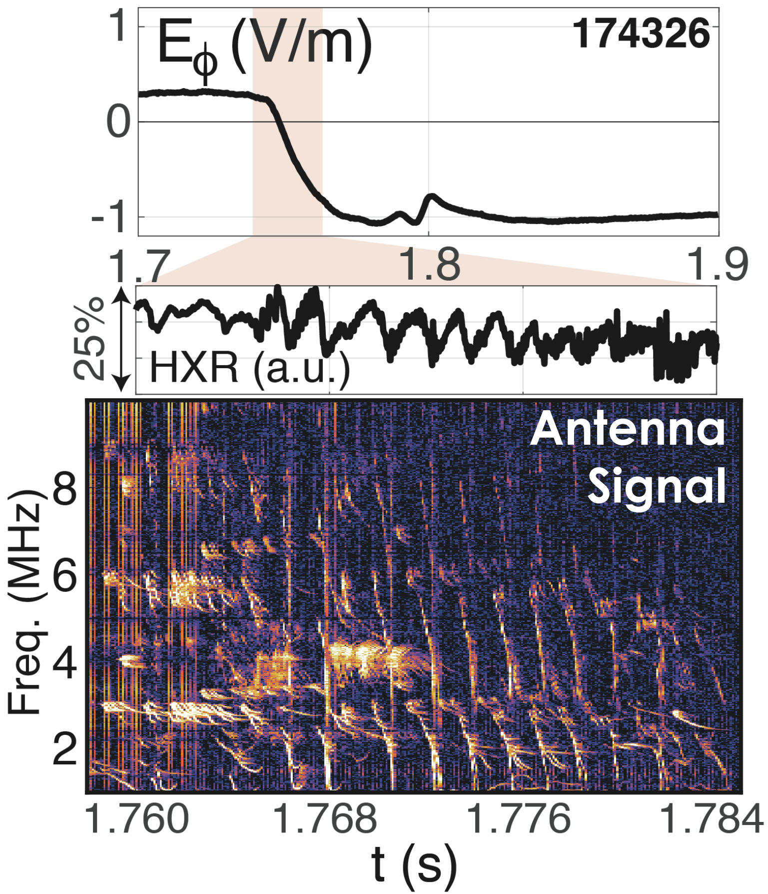
D_2 Injection Enables Observation of Natural Kinetic Instability in Few-eV Post-Disruption RE Plateau

- **Natural instability observed in post-D_2 RE plateau, but so far only with large applied electric fields**
  - Indicates natural RE distribution function is stable in DIII-D

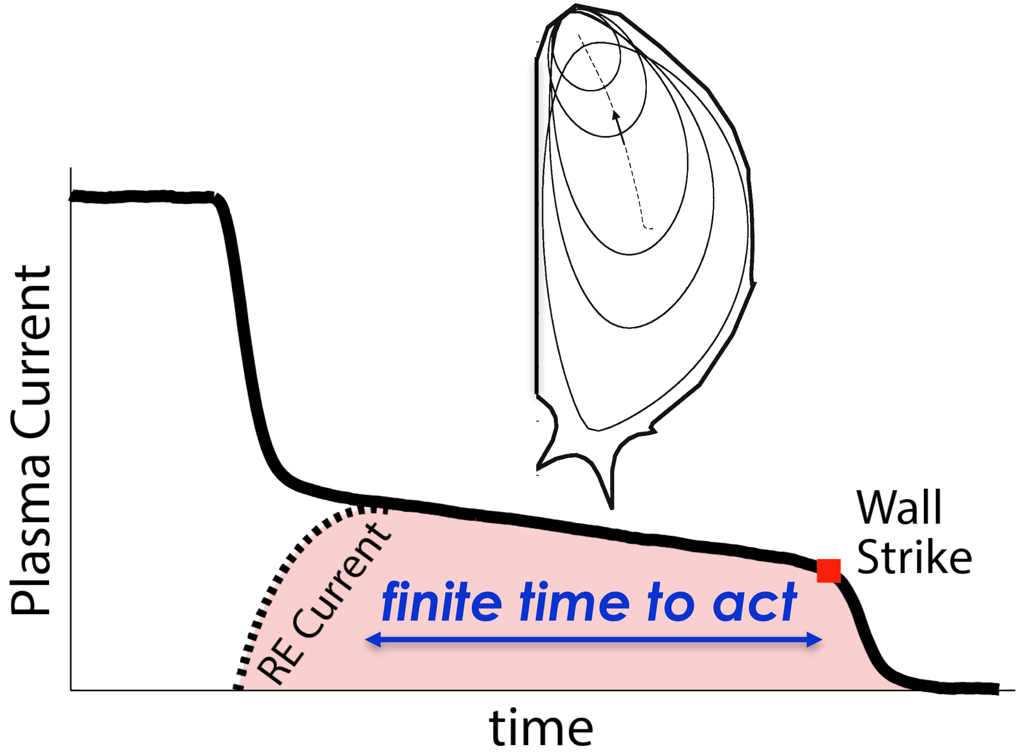
- **Area for future work, alongside RF antennas for active launch**

Active and passive methods under study



Dissipation via Secondary Injection Must Happen Faster than Vertical Instability Loss Rate

- **ITER RE beam will be vertically unstable**
  - Finite time to dissipate RE



K. Aleynikova et al, Plasma Phys. Rep. 2016

Dissipation via Secondary Injection Must Happen Faster than Vertical Instability Loss Rate

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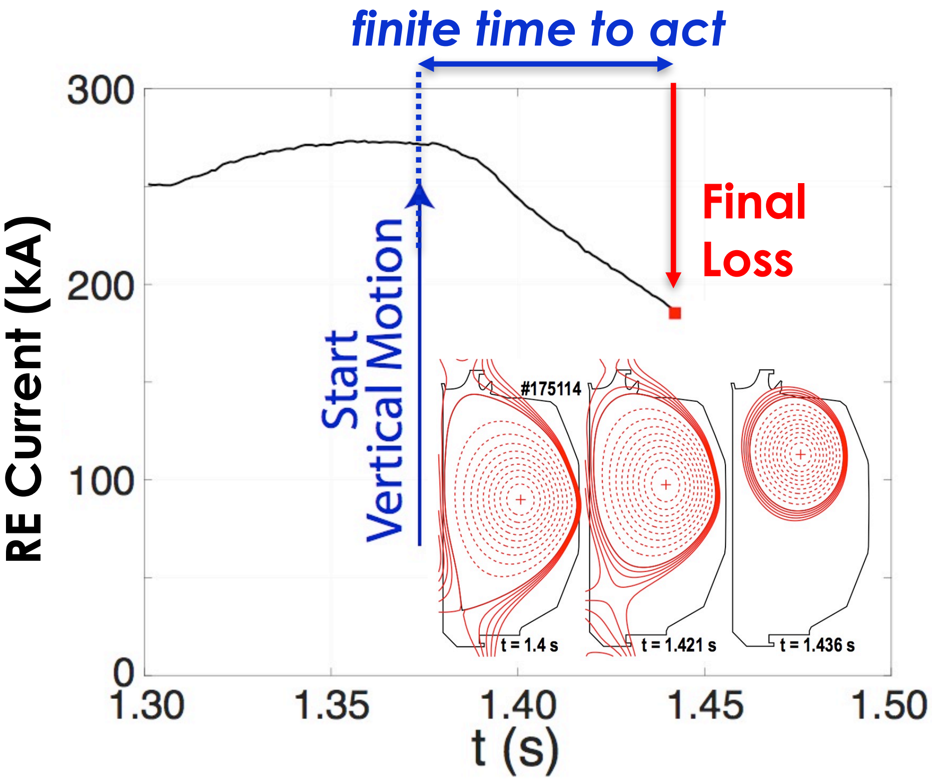
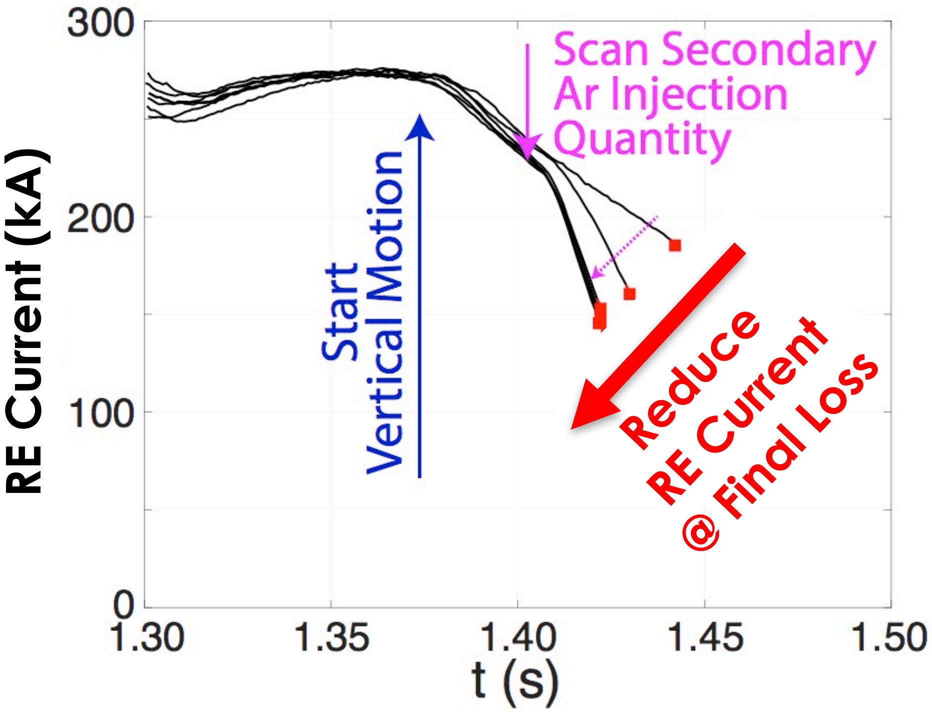
- **DIII-D has developed vertically unstable RE beams to address key physics questions**



RE Current at Final Loss Can Be Reduced with High-Z

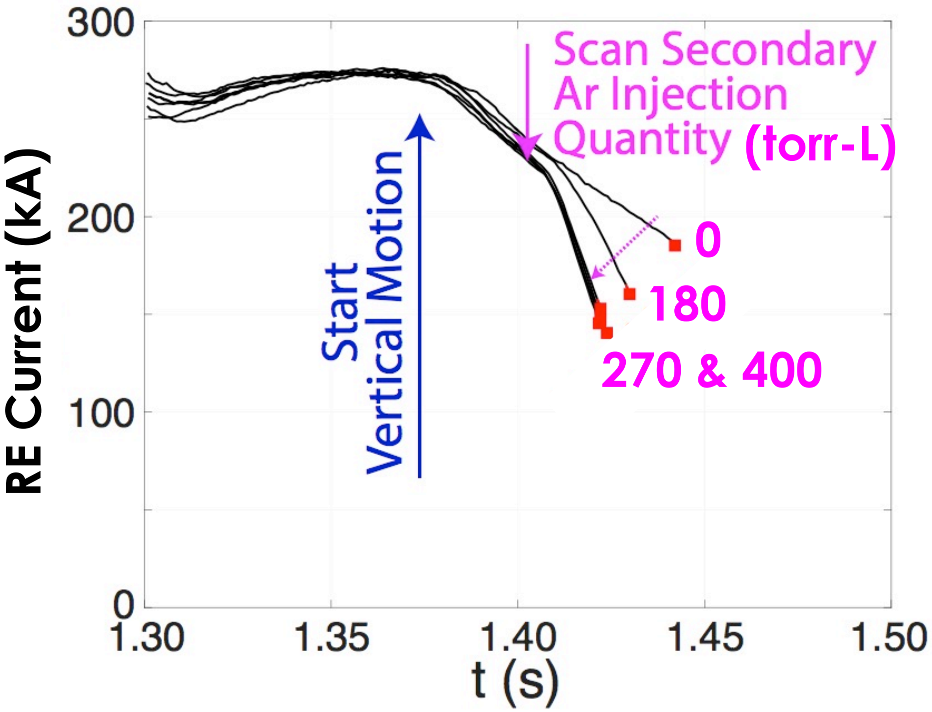
- **Reduced RE current at final loss achieved by increasing Argon quantity**



RE Current at Final Loss Can Be Reduced with High-Z … but Saturation of Dissipation Observed

- **Reduced RE current at final loss achieved by increasing Argon quantity**
- **RE dissipation *saturates* at given Ar quantity**
  - *Upper bound on assimilation*
  - Universal observation[1,2,3]

Possible show-stopper for high-Z dissipation

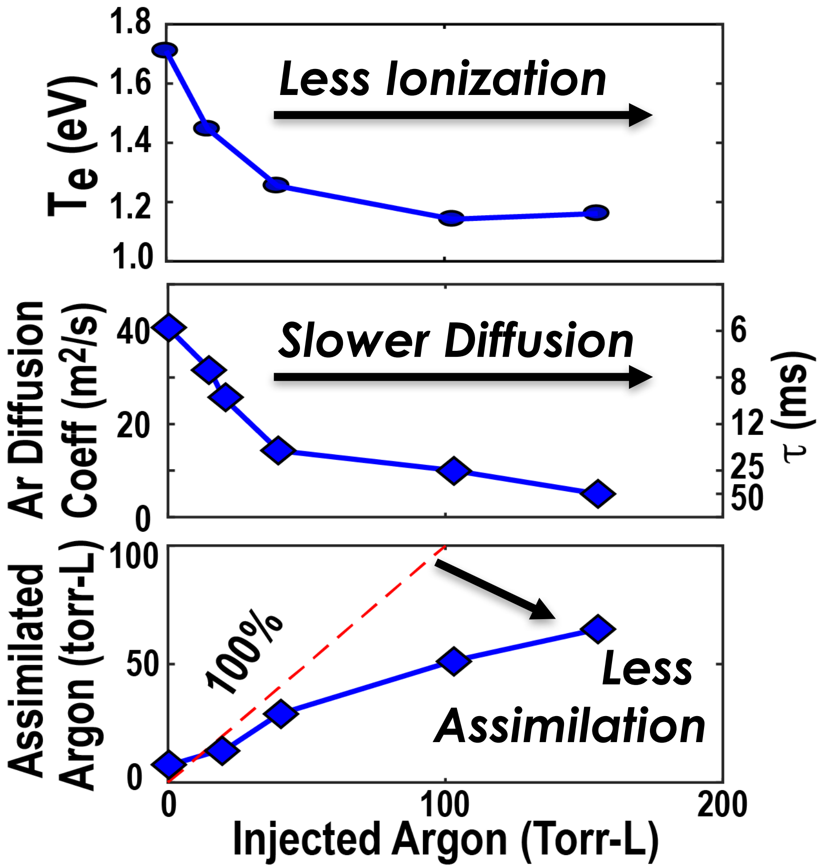


[1]C. Reux et al, NF 2015, [2]G. Papp, IAEA 2016
[3]Z.Y. Chen, ITPA 2017

Saturation of Dissipation Linked to Ionization Power Balance: Temperature Effects Can Slow High-Z Diffusion

- **Ionization of large Ar quantities causes significant T_e drop**
- **Lower temperature and higher Ar density reduces diffusion coefficient**
  - Classical diffusion goes like T / n
- **Vertical loss happens faster than Ar can diffuse: not enough time**
  - Observed dissipation saturates

RE dissipation depends on ionization power balance



E. Hollmann et al, NF (in prep)

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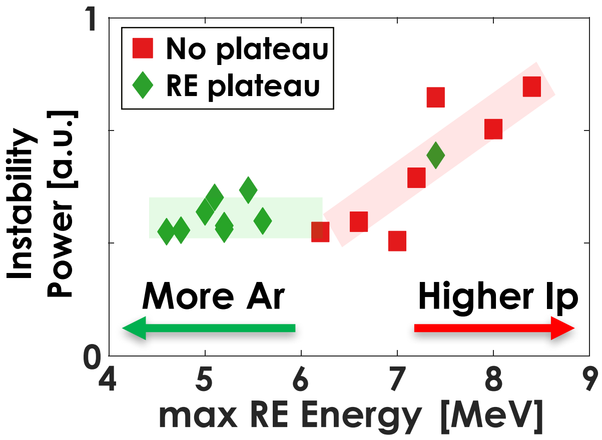
Important Advances in RE Experiments and Modeling are Improving Predictive Capability for ITER DMS Design

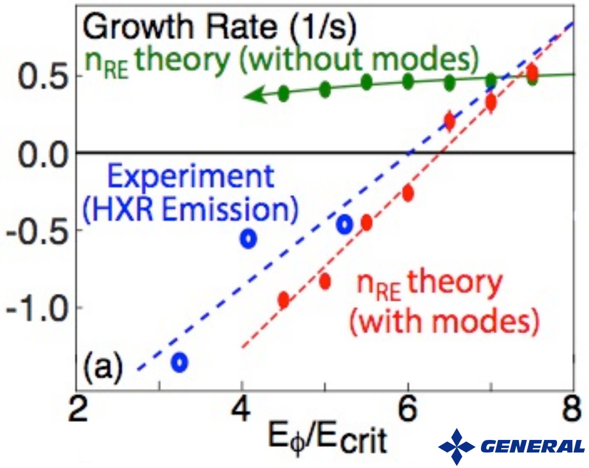


RE Avoidance:

- **Modeling does not yet predict RE seed**
- **Kinetic instability may explain threshold dependence on I_P and Ar quantity**

RE Mitigation:

- **Including kinetic instability in modeling reproduces elevated E/E_{crit} threshold**
  - Application to disruption under study
- **High-Z dissipation saturation linked to ionization power balance**



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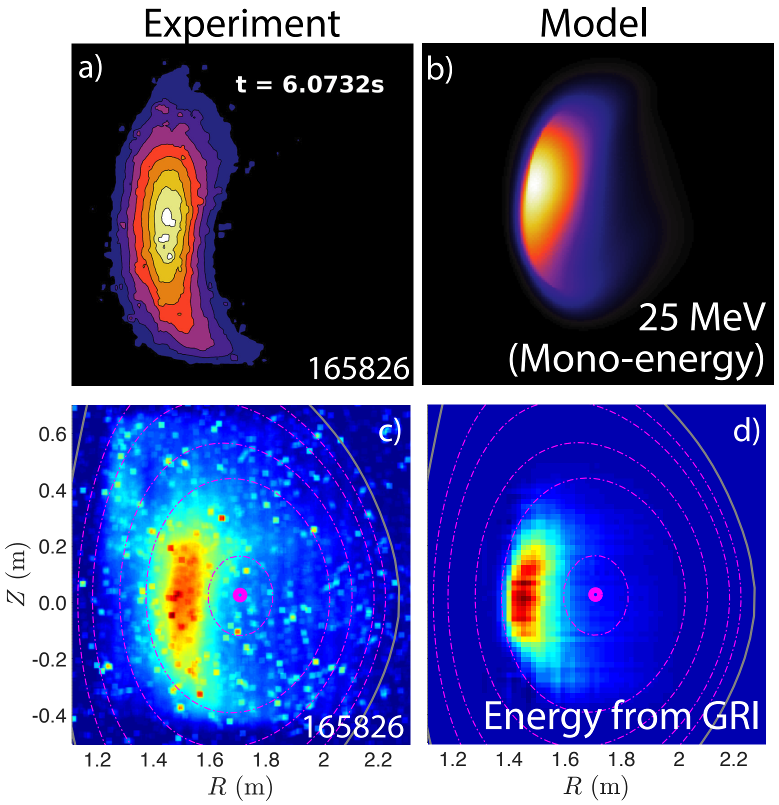
Bonus Slides

Model Validation Using Synchrotron Emission Images Explores Pitch-Angle and Spatial RE Dynamics

- Agreement with experiment seen in multiple simulations

- Pitch-angle distribution is not what 0-D Fokker-Planck models would predict

- See later talk for more information

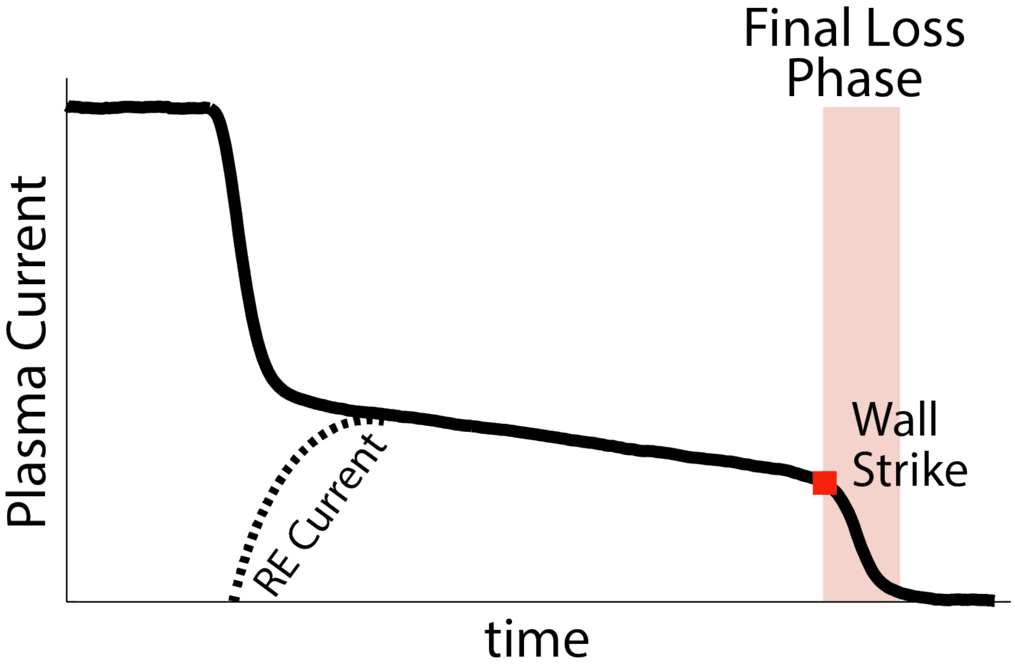


D. Del-Castillo Negrete, TH/4-3

M. Hoppe et al, NF 2018
L. Carbajal et al, PoP 2018

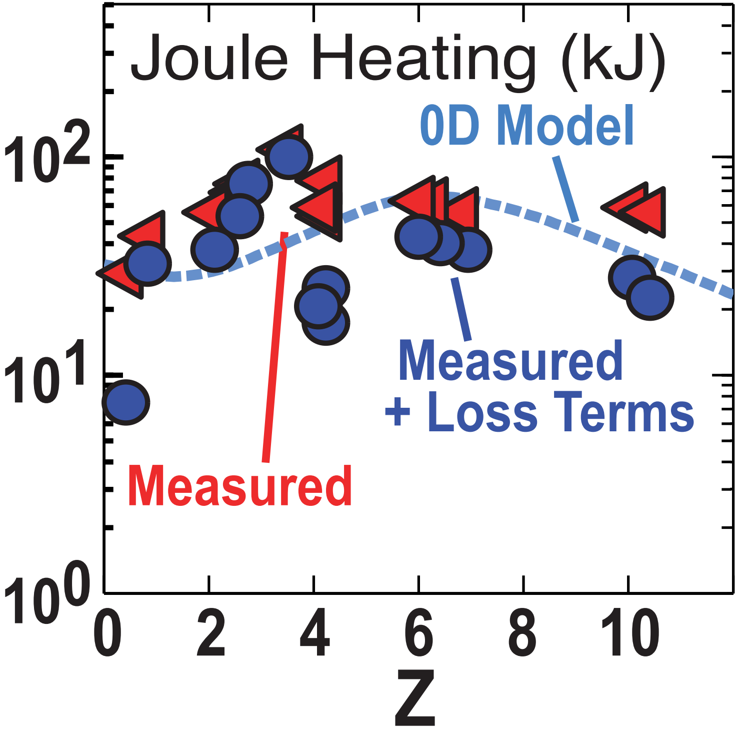
Dynamics of Final Loss Phase Sets Ultimate Requirement for RE Mitigation

- **What final RE current is tolerable?**
- **Can we predict the heating of the first-wall?**



Joule Heating of First-Wall from RE Strike Can Be Predicted as well as its Z-dependence

- 0-D circuit model[1] developed to predict Joule heating of wall from RE strike
- RE loss time required input, measured in DIII-D
- Model successfully captures total heating and Z-dependence



0-D Model Successful
Local Estimates are Future Work

[1]R. Martin-Solis, NF 2017
E.M. Hollmann et al, NF 2017